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Thermal Gradient Effects On Thirteen Flush Mounted Pressure Transducers

DEPARTMENT OF COMMERCE ★ NATIONAL BUREAU OF STANDARDS ★

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Thermal Gradient Effects on Thirteen Flush Mounted Pressure Transducers

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Thirteen different flush mounted pressure transducers of seven manufacturers were tested by creating a thermal gradient in them and recording the resultant zero shifts. Photographs of typical outputs are shown and the results are compared. A typical recording shows these general characteristics; 1. a very rapid change in output reaching a peak in a second or less, 2. a more gradual shift which reaches a peak in a time which may be a few seconds or more than a minute, and 3. a shift in reading which remains as long as the gradient is maintained. Examples were found in which each of these were positive or negative. The magnitude in a few cases was small, in many was a large fraction of its range, and in one case well in excess of the full scale range.

KEY WORDS: Temperature, thermal gradients, pressure transducers, response, zero shift, pressure measurement errors.

1. Introduction

The effects of thermal gradients on the zero outputs of thirteen commercial pressure transducers have been studied.[1] Since the total number of transducers studied is not sufficient for a statistical evaluation, nor any segment large enough to be representative of a type of transducer or of a particular manufacture's transducers, the results are only indicative of the range of performance that may be encountered. We have studied transducers of similar design but of different manufacture as well as those of different design of the same manufacture.

To provide the user with a basis for judging whether a particular pressure transducer will meet the requirement of his application, the transducer manufacturer specifies the performance of the instrument over a range of temperature in which valid results may be expected. Effects of temperature on sensitivity and on zero-pressure response are usually specified. In the majority of transducers a shift of the zero-pressure response equal or less than 0.02% of full scale per degree Fahrenheit is specified.

Customarily these specifications of temperature-range performance of pressure transducers refer to equilibrium conditions, that is, to conditions in which temperature is uniform throughout the transducer. In standard temperature tests as recommended by the Instrument Society

[1]Response of Flush Diaphragm Pressure Transducers to Thermal Gradients Preprint No. 13.3-4-65 ISA 1965.

of America one waits for a constant temperature to be established within the transducer before recording its output. Since equilibrium conditions do not always exist at the time of measurement in many applications, the validity of this type of temperature test alone to determine the temperature performance characteristics of pressure transducers is open to question. One can expect to find variations in temperature occurring during the measurement process, often caused by the same process that produces the pressure being measured.

A change in temperature can alter the output of a pressure transducer by changing its damping and thus its dynamic response; by altering its sensitivity and thus its output; by altering its zero-pressure output and thus the calibration base line. The study reported here investigated the influence of thermal gradients on the zero response of pressure transducers as distinct from those of changes in uniform temperature. Conditions of observation were such that no part of the instrument was exposed to a temperature greater than its proper operating range.

A word of caution should be noted. For instruments of the type tested (the flush mounted diaphragm pressure transducer) one could be dealing with the effects on the output due to: (1) A steady state gradient through the instrument. This is encountered in high speed aircraft by instruments installed between the cooled interior and the exterior which is heated by air friction; also by instruments installed near the engines of conventional aircraft (the gradient can be in any direction), or (2) A changing ambient temperature uniform in space; this, because the various components of the instrument follow the temperature change with different lags. In addition, even though an instrument has been designed to cope with both of the above conditions it still has to cope with changes with time in the gradient of temperature in the instrument, and or (3) Short term non-steady-state gradients in the environment. (Caused in many cases by the phenomena that is generating the pressure being measured.) While these tests are specifically aimed at conditions of temperature gradients in one particular direction, for gradients in different directions one can expect comparable effects and they should be investigated by the user.

2. Test Equipment

To evaluate the effects of thermal gradients on pressure transducers, a device capable of establishing thermal gradients in flush mounted pressure transducers was built.

An electric soldering iron was altered to serve as the heat source for generating gradients. Heat is transferred to the transducer by conduction through the thermal contact of the converted iron with a pool of molten Wood's metal. With the addition of an insulation shield and means for measuring and controlling heat output, the converted iron was found capable of transfer of 35 kW/m^2 at (107°C) 225°F and 318 kW/m^2 at (482°C) 900°F. During a run, the temperatures of all the major components of the

test are continuously monitored, and the thermal output of the heater can be altered by adjusting the input voltage to the heater.

Figure 1 shows the test assembly. The pressure transducer can be seen at (A). It is held by an insulated clamp (B). During the test its surface is just immersed in the liquid Wood's metal pool (C) which is used as heat transfer medium. The heater voltage is controlled by an adjustable autotransformer (D). Thermocouples (E) are used to measure the temperature of the Wood's metal and of the front and back surfaces of the transducer. A recorder is used to keep multiple continuous records of temperatures during the test. The electrical output of the transducer is displayed on an oscilloscope and photographed.

3. Test Program

Each transducer was first checked using the standard series of uniform temperature tests[2] in order to compare its performance with that listed in the manufacturer's specifications; all were found to be within specifications.

The gradient test produces a temperature gradient within the pressure transducer with the high temperature region at the pressure sensing end. In a typical test series the temperature of the heat source was increased in steps, running one test at each step, until the specified limiting operating temperature of the transducer was reached. The temperature of the sensing end and the back of transducer and the zero level output were recorded during each run.

The tests to date have been limited to a maximum front surface temperature of 600°F (315.5°C). A heat influx of approximately 225 kW/m^2 was required to achieve this temperature.

4. Test Results

A typical thermal gradient zero shift curve from a flush diaphragm type pressure transducer, Figure 2 (a), shows the following:

1. A very rapid change in output reaching a peak in a second or less (in this instance a negative peak value).

2. A more gradual shift which reaches a peak in a time which may be a few seconds or more than a minute.

3. A shift in zero reading which tends to level off toward some value which may remain as long as the gradient is maintained. In this instance the maximum zero shift was not in the same direction as the initial peak shift.

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[2]NBS Technical Note #411, February 9, 1967, Methods for Performance-Testing of Electromechanical Pressure Transducer, P. S. Lederer.

The initial portion of the curve has been interpreted as "oil canning," the differential expansion and "popping" of a diaphragm held by a rigid hoop. In general, this is observed as a rapid response, i.e., "oil canning" can occur in less than one second. It varied from +2.0% FS (full scale) to -30% FS and appeared to be least in those instruments that showed the smallest zero shift.

Figures 2a and 2b show the effect of what is being called "oil canning" in the output of two different transducers. Figure 2b shows an unusually large effect. It, and the maximum zero shift are closely related in this instance and represent the largest response of the kind observed. Figure 3a is included to show the possible response speed of such behavior. For this transducer, a piezoelectric type, a change of 1.9% FS (in this instance, 332 kN/m^2) occurred in a fraction of a second.

The photographs of the shifts of the zero level outputs of the various transducers have been given effective gradient numbers which represent the transducer's position in the ordered sequence of effective gradient sensitivities. The photographs represent typical zero-shifts and were not chosen for maximum test conditions. The test temperature is given alongside each photograph. It was noted that while duplicate transducers tested (Figure 3, photographs (b) and (c) same model series number and range) under duplicate conditions gave similar results, some units of the same manufacturer and same series but of different pressure ranges did not. (Figure 4, photographs (a), (b), and (c) are of the same model series but of different ranges.)

On all the transducers tested, as long as a gradient existed, a zero shift was observed and a zero shift steady state condition could be approached. Photos, Figures 6a, 6b, and 6c, are particular examples of this condition.

Excluding the initial pulse, a separation of the thirteen observations into two patterns can be noted. The division is between those whose zero shift maximizes within the test period and those tending to show a gradual increase with time (see remarks in Table 4). Since maxima were observed only in compensated transducers, it is suggested that placement of the temperature compensating elements may be responsible.

The maximum zero shifts and response time of the different transducers are listed in Table 4. It was noted that an increase in the rate of heating from 35 kW/m^2 to 350 kW/m^2 did not alter the time required to reach maximum zero shift in the tests, although the increase did alter the gradient and the magnitude of maximum zero shift.

A review of the data taken during all the tests indicated that the gradient induced during a particular transducer test is related to the temperature of the hot pool with which the transducer is in contact and the length of time it has been immersed. The numerical value of the maximum zero shift thus depends to a great extent of the test conditions.

5. Analysis

An example of the analysis of one particular transducer involving an intermediate rate of thermal gradient is as follows. The empirical relationship, $Z = A° \cdot \mu + X_j\ (A° - B°)$, was found to hold for the conditions over which flush mounted pressure transducers were tested.

where Z = zero output as % FS,

where μ = manufacturer's thermal coefficient per degree,

where A = temperature of front surface of the transducer,

where B = temperature of back exposed surface of the transducer,

and X_j = correction coefficient for the specific condition of the test and particular transducer (j).

In order to find the numerical value of the correction coefficient X for a particular pressure transducer, one makes a gradient temperature run with the transducer held at a measured temperature A at the active front surface, and records the temperature B of the exposed back surface and the zero pressure level output of the transducer. The values of A,B and the manufacturer's specification for zero output as a function of operating temperature is then used in the equation. One solves for X.

One assumes that if the experimental setup is similar to that expected in the intended test, the value of X derived can be used to determine the percent of full scale zero shift that will occur under the thermal condition of the actual test. Although the value of X derived was determined by the average of five points taken during one previous run, Table 2 is composed of data from six different runs picked because they provided examples of differences in operating procedures that covered the entire testing temperature range and measured zero shift. Run number 1 was made on a unit which initially was slightly above room temperature and cooled by convection, i.e., no provision being provided for additional air cooling. Runs numbered 2, 3, and 5 were initially at room temperature and cooled by convection currents. Runs numbered 4 and 6 were initially at room temperature and were cooled by forced air. A fan directed room air on the exposed back of the transducer during the test.

The relationship % FS zero shift = A · (manufacturer's coefficient per degree) + X(A - B) is based on the limited data taken from the thermal gradient measurements of thirteen different transducers. It is limited in use to the zero shift after oil canning for various conditions of front surface temperatures and resultant temperature gradients. It was found to be correct to ±10% for the flush diaphragm pressure transducers tested.

The following example illustrates the procedure to be followed in using the correction for a transducer under test. In this instance, temperatures in °F are used to conform to the customary practice of

manufacturers in publishing transducer specifications. The empirical relationship found for the gage of Figure 2c was 0.02% FS/°F (manufacturer's specification) plus 0.30% FS/°F (thermal transient test, correction coefficient derived). One would therefore multiply 0.02 by the temperature A of the front surface and then add the differential term 0.30 (A - B) where B is the temperature of the back surface of the transducer. One would then convert from % FS to psi and subtract this value from the recorded pressure. The result would be the pressure ±10%, that would have been recorded if no thermal gradient had existed. In this way correction is made for the zero shift of the transducer after the first few seconds, provided the front and back temperatures of the transducer have been monitored. An additional correction may be necessary due to a change in sensitivity with temperature, although the error from this source was not important in the devices that have been tested.

6. Effective Gradient Sensitivity

In order to allow comparisons among transducers tests at different temperatures and with resultant different gradients, a relative "effective gradient sensitivity," (EGS) was calculated. The effective gradient sensitivity was defined by dividing the maximum zero shift, in percent of full scale, by the temperature difference between the hotter surface of the transducer and the reference temperature for zero shift of the transducer. The results are listed in Table 3 in terms of % FS/°F and % FS/°C.

Since all the transducers were given the same kind of test, in each case to the limit of the expected normal operating temperature, these values (EGS) represent a measure of ability to perform while exposed to thermal gradients. A transducer that has an EGS value that is equal to or less than the manufacturer's specifications for zero shift with temperature can be considered to be unaffected by thermal gradients.

7. General Comments

As indicated in the earlier study[3] and verified by the tests reported here, design differences can be more important than the kind of active element used in the transducer. Although both of the manufacturers of the two pressure transducers used to obtain the test results shown in Figures 4 and 5 used unbonded strain gages as their active elements, the zero-shift response to thermal gradients differed widely.

The photographs in Figures 5a and 5b show the results of thermal gradient tests on two transducers produced by the same manufacturer eleven years apart. During this time, 1954 to 1965, the specification

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[3]loc cite.

for the upper operating temperature limit changes from 165°F to 250°F and the zero shift specification was reduced from 0.08 to 0.015% FS/°F.

Some of the factors that govern the effect of a temperature gradient are: the mass of the section exposed to the heat, i.e., the thermal inertia of the case, the thermal path differences that exist between the active elements and the compensating elements, the thermal alterations of strain members, and changes in spring positions due to temperature gradients in the supports. In addition, one could expect zero shifts to result from "oil canning," leverage shifts due to unequal expansion of parts, and variations in electrical and physical properties with temperature. These factors need to be considered in attempting to reduce or avoid the effect of thermal gradients.

To avoid the zero shift that is due to deformation requires a design that allows for the thermal differences that are expected or are possible. Balanced and compensated mechanical motions and thermal buffers for sensitive springs and flexures are possibilities. Fused Quartz or sapphire rods for extensions to provide relatively constant dimensions and still provide poor conduction of the heat would seem to be one way of removing the active elements of the transducer from the immediate vicinity of the heat source, thus producing a relatively constant environment that tends to isolate and protect the active elements for short period of time.

One can transmit the pressure to be measured by tubes to a cooler region (with altered dynamic characteristics), or cool the active elements of the transducer by external means.

A compromise that would provide the equivalent of a uniform temperature zone for the transducer would consist of uniformly preheating the transducer to within a few degrees of the expected working temperature just before the test.

8. Summary

Studies of the effects of thermal gradients on performance of pressure trandducers indicate that: 1. Flush diaphragm pressure transducers may show very large zero shifts due to thermal gradients even though they are compensated for changes in uniform temperatures. 2. For the thirteen units tested, the detailed design is as important as the principle used to convert diaphragm deflection to an electrical output signal, i.e., piezoelectric crystal, wire strain gages, bonded or not, differential transformer, etc. 3. Some transducers can operate in a thermal gradient with very little zero shift, but no simple way to predict this without testing is apparent at this time.

Since the transducer's zero shift in this test is the result of an imposed thermal gradient and is a function of the transducer design, a comparison of responses to thermal gradients reflects the comparison of transducer design features.

For the transducers tested, although the rate of energy input and thermal flux density influenced the magnitude and the time to reach a given gradients, it is the temperature gradient itself that is responsible for the zero shift of the instrument and this should be considered when choosing a pressure transducer for field use.

The wide range of response that was encountered in these tests emphasized the need for caution in interpreting the data furnished by pressure transducers when thermal gradients may be present. While these tests specifically aimed at conditions of temperature gradients in one particular direction, for gradients in other directions one can expect comparable effects and they should be investigated by the user.

TABLE 1

Oil Canning

	Transducer Type	Pressure Range	% FS	Time to Reach Maximum (Seconds)
(A)	Unbonded wire strain gages (damped and un-damped)	0-300	- 1.0	8.0
	Unbonded wire strain gages (damped and un-damped)	0-1000	- 3.0	8.0
	Unbonded wire strain gages (damped and un-damped)	0-50	- 1.0	1.0
	Unbonded wire strain gages (damped and un-damped)	0-15	-30.0	2.0
(B)	Bonded strain gages damped	0-500	- 8.0	1.0
(C)	Semiconductor strain gages	0-100	+ 2.0	1.0
	Semiconductor strain gages	0-100	+ 1.8	1.0
(D)	Unbonded strain gage	0-150	-23.0	1.0
	Unbonded strain gage	0-50	-10.0	0.1
(E)	Variable inductance	0-100	- 2.5	1.5
	Variable inductance	0-100	- 5.0	1.5
(F)	Linear differential transformer	0-500	none noted	
(G)	Crystal	0-3000	- 1.8	0.1

TABLE 2

Thermal Gradient Response

Temperature Front Measured	Temperature Differential Measured	Zero Shift % FS Computed	Zero Shift % FS Measured
(A)	(A-B)	0.02(A) + 0.3(A-B)	
228°F	47	19	18
180°F	63	23	25
300°F	60	24	25
253°F	120	41	44
545°F	120	47	49
360°F	160	55	50

TABLE 3

Effective Thermal Gradient

Figure Number	Transducer Type	Pressure Range PSI	EGS % FS/°F	EGS % FS/°C	Manufacturer's Specifications % FS/°F	Manufacturer's Specifications % FS/°C
4a	Unbonded wire strain gages (damped and undamped)	0-300	0.004	0.007	0.01	0.018
4b	Unbonded wire strain gages (damped and undamped)	0-1000	0.01	0.02	0.01	0.018
7	Semiconductor strain gages	0-100	0.01	0.02	0.01	0.018
6	Variable Inductance	0-100	0.018	0.03	0.01	0.018
3	Crystal	0-3000	0.03	0.05	0.01	0.018
3b & c	Bonded strain gages damped	0-500	0.043	0.08	0.01	0.018
6	Linear Differential Transformers	0-500	0.073	0.13	none	
2	Unbonded strain gages	0-150	0.083	0.15	0.02	0.036
5b	Unbonded wire strain gages (damped and undamped)	0-50	0.10	0.18	0.015	0.018
5a	Unbonded wire strain gages (damped and undamped)	0-50	0.14	0.15	0.04	0.072

TABLE 3 (Continued)

Figure Number	Transducer Type	Pressure Range PSI	EGS % FS/°F	EGS % FS/°C	Manufacturer's Specifications % FS/°F	Manufacturer's Specifications % FS/°C
2b*	Unbonded wire strain gages (damped and undamped)	0-15	0.16	0.19	0.01	0.018
4c*	Unbonded wire strain gages (damped and undamped)	0-50	0.50	0.9	0.01	0.018

Figure 5a Received 1954
Figure 5b Received 1965

*The last two transducers require special mention. The 0-15 PSI gage did return to manufacturer's specifications during the test within 50 seconds after the introduction of heat. The 0-50 PSI appears to have a loose connection which separated under the stresses developed by a thermal gradient. The transducer did not show any abnormal output for any of the standard tests and checked out within the manufacturer's specifications in the normal temperature tests, both before and after the thermal gradient tests. (See photographs 2b and 4c.)

TABLE 4

Response To Thermal Gradients

Transducer Type	Pressure Range PSI	Test Temperature °F	Maximum Zero Shift % FS	Time at Which Maximum Occurs in Seconds	Remarks
A	0-15	200	- 32	1-3	Recovers to less than 3% FS by 51 seconds
	0-50	230	>+100	30	After peak goes off scale requires 10 minutes to recover
	0-300	212	+1.0	50	After peak at 50 seconds recovery starts
	0-1000	400	+4.0	180**	Maximum shift increases with time
	0-500	600	- 26	20	After peak
B	0-500	600	- 26	20	After peak at 20 seconds recovery starts
C	0-100	190	-2.0	31	After peak at 31 seconds recovery starts
	0-100	190	-2.0	81*	
D	0-150	600	+ 49	51	After peak at 51 seconds recovery starts
	0-50	160	+ 22	10	After peak at 10 seconds recovery starts
	0-50	250	+ 26	8	After peak at 8 seconds recovery starts
E	0-100	250	+6.0	180**	Maximum shift increases with time
F	0-500	320	+ 23	180**	Maximum shift increases with time
G	0-3000	373	- 10	7	After a peak at 7 seconds starts to recover (test was limited to 20 seconds)

*Test Limited to 81 Seconds.
**Test Limited to 180 Seconds.

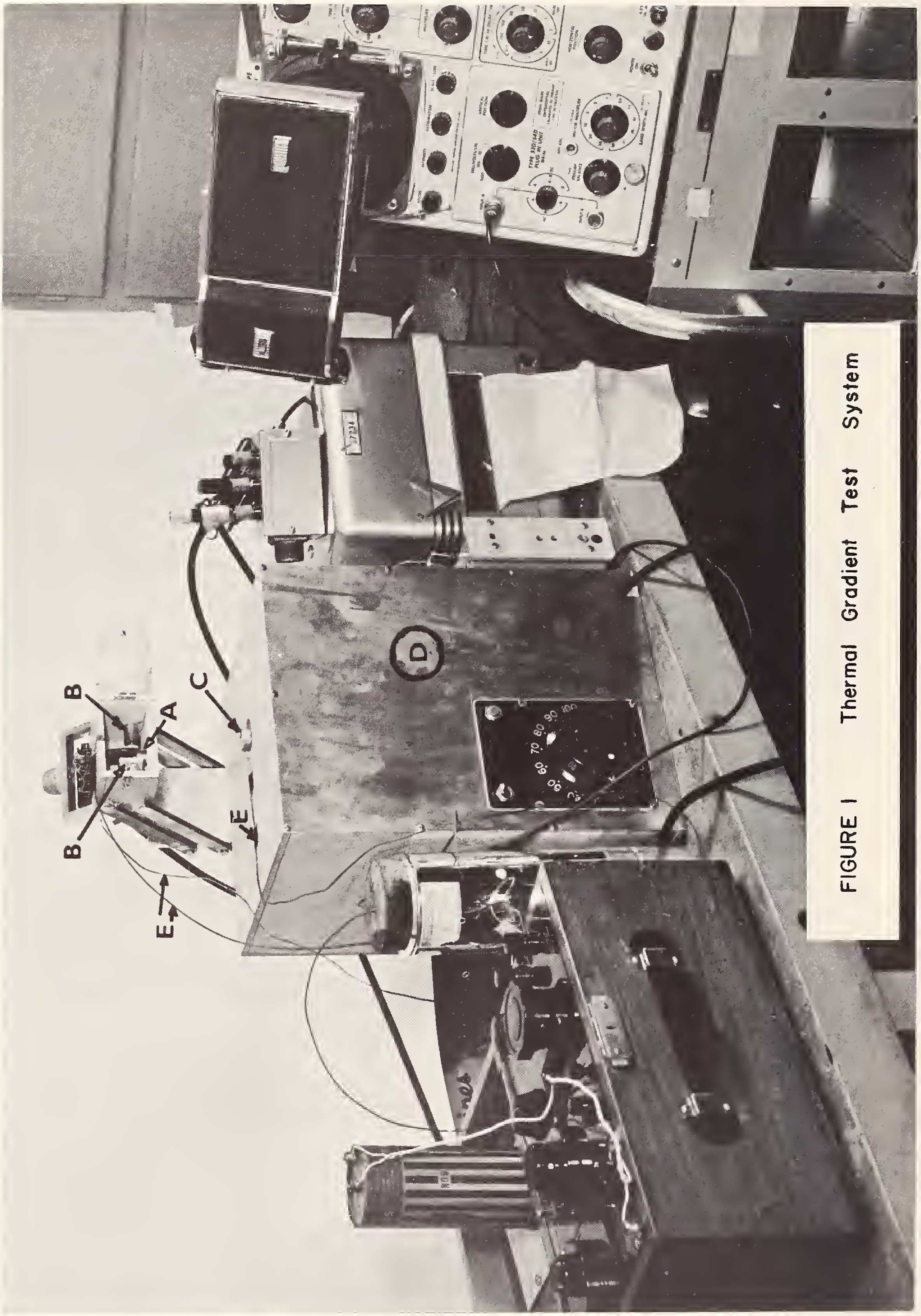
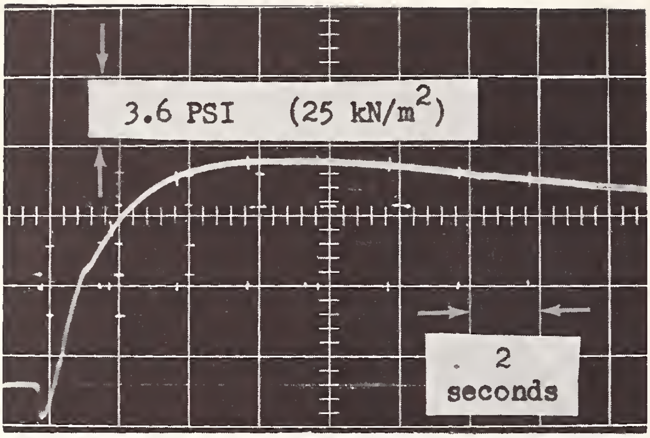


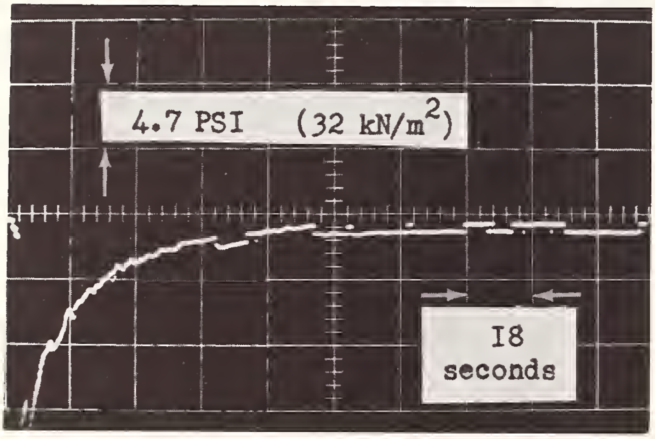
FIGURE I Thermal Gradient Test System

Figure 1A Gradient Heater



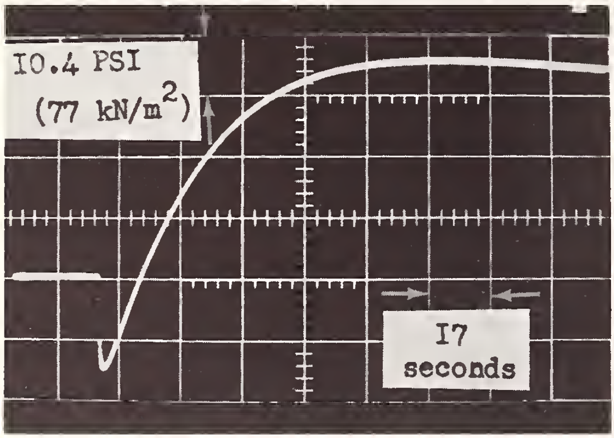
(a)

Unbonded Strain Gage
0-50 PSI
Time 2 S/cm
Temp. 165°F 74°C
Max Zero Shift + 23% FS



(b)

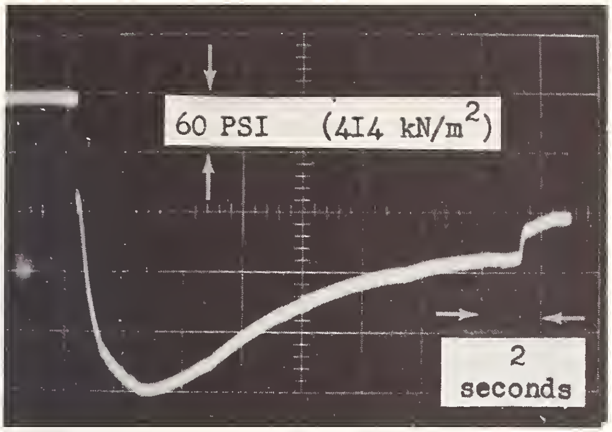
Unbonded Strain Gage
0-15 PSI
Time 18 S/cm
Temp. 200°F 93°C
Max Zero Shift - 32.7% FS



(c)

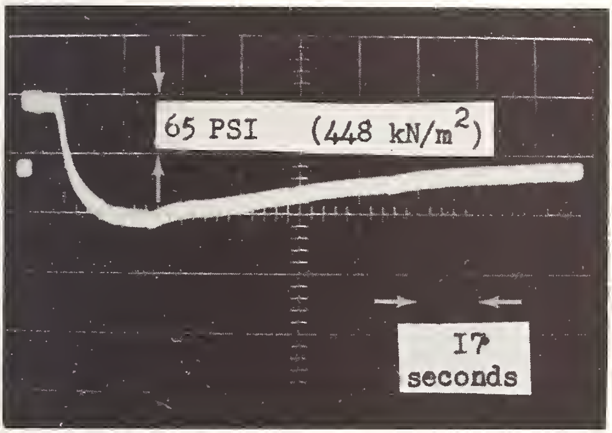
Unbonded Strain Gage
0-150 PSI
Time 17 S/cm
Temp. 200°F 93°C
Max Zero Shift + 25% FS

Figure 2 Thermal Gradient Response



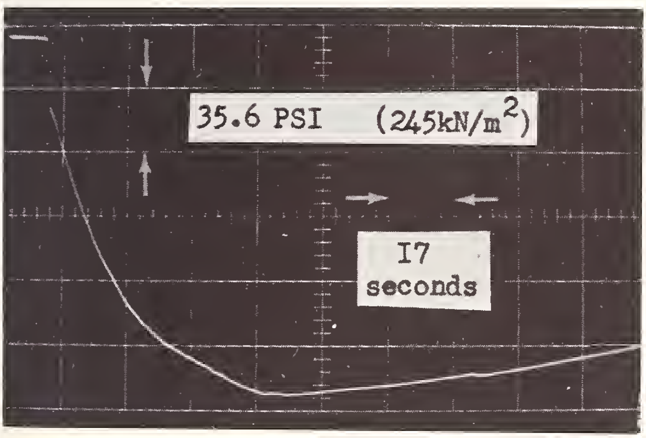
(a)

Crystal
Range 0-3000 PSI
Time 2 S/cm
Test Temp. 373°F 189°C
Max Zero Shift - 10% FS



(b)

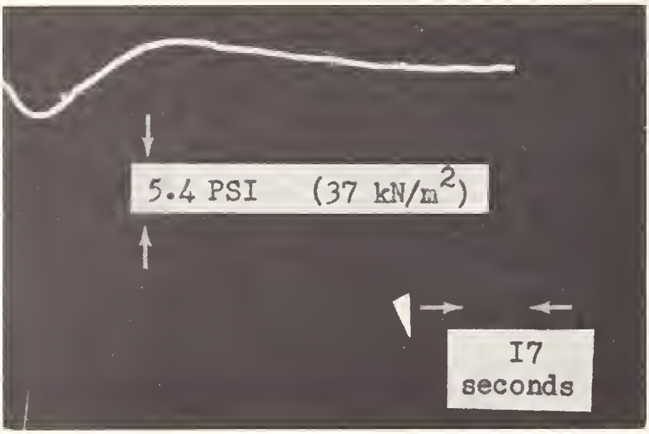
Bonded Strain Gage
Range 0-500 PSI
Time 17 S/cm
Test Temp. 600°F 316°C
Max Zero Shift - 26% FS



(c)

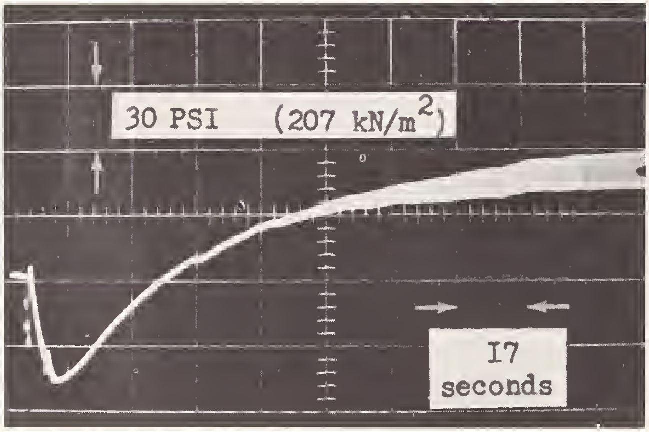
Bonded Strain Gage
Range 0-500 PSI
Time 17 S/cm
Test Temp. 600°F 316°C
Max Zero Shift - 25.6% FS

Figure 3 Thermal Gradient Response



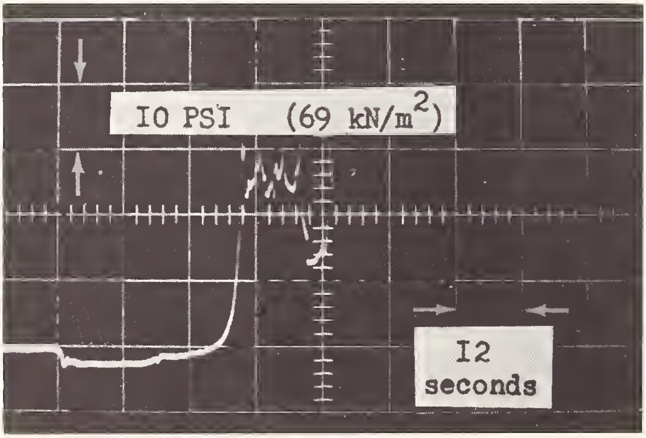
(a)

Unbonded Strain Gage
Range 0-300 PSI
Time 17 S/cm
Test Temp. 212°F 100°C
Max Zero Shift 1.3% FS



(b)

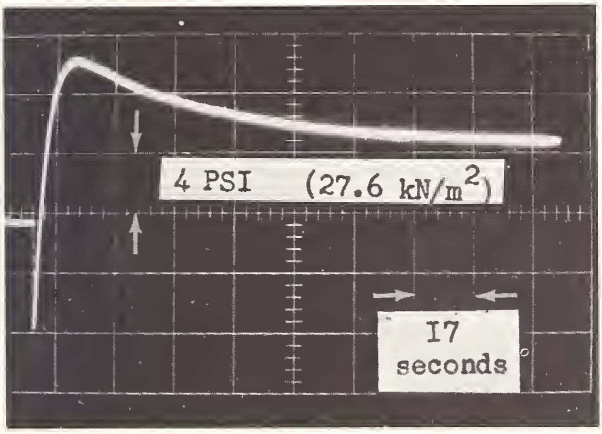
Unbonded Strain Gage
Range 0-1000 PSI
Time 17 S/cm
Test Temp. 400°F 204°C
Max Zero Shift 4% FS



(c)

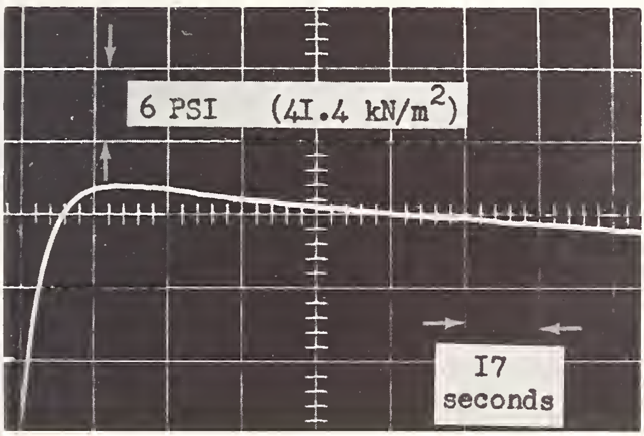
Unbonded Strain Gage
Range 0-50 PSI
Time 12 S/cm
Test Temp. 230°F 110°C
Max Zero Shift + 100% FS

Figure 4 Thermal Gradient Response



(a)

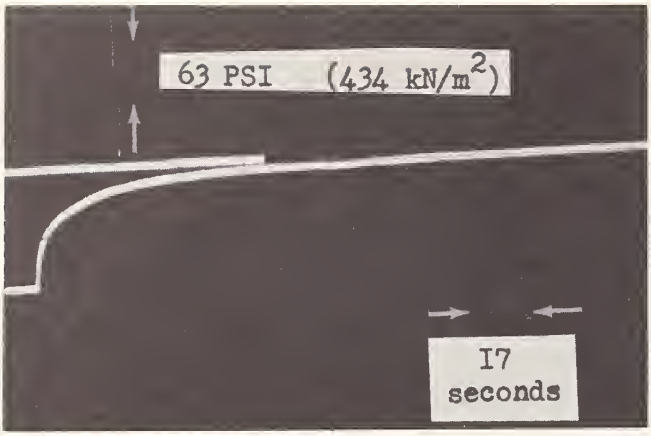
Unbonded Strain Gages
Range 0-50 PSI
Time 17 S/cm
Test Temp. 100°F 74°C
Max Zero Shift 23% FS



(b)

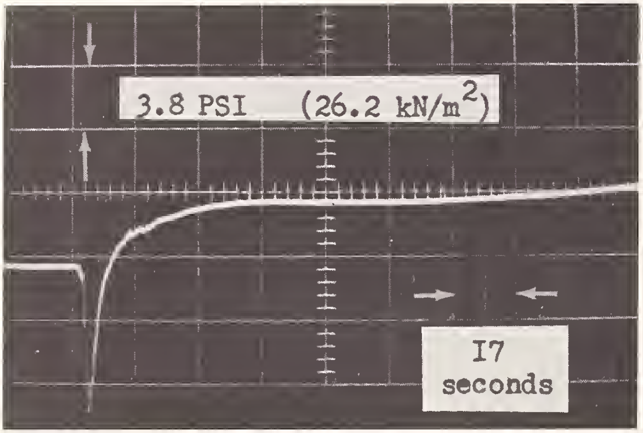
Unbonded Strain Gages
Range 0-50 PSI
Time 17 S/cm
Test Temp. 231°F 111°C
Max Zero Shift 30% FS

Figure 5 Thermal Gradient Response



(a)

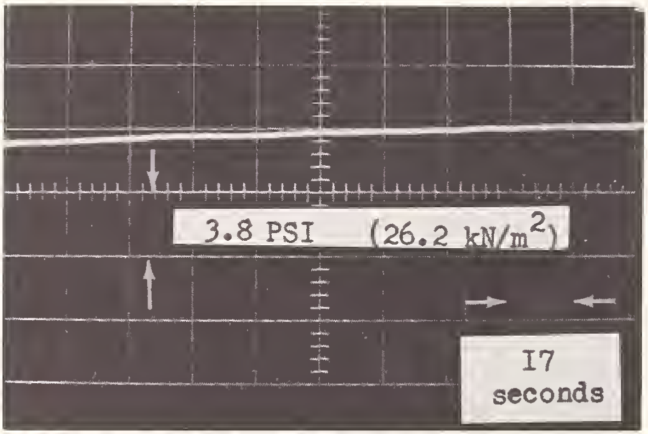
Differential Transformer
Range 0-500 PSI
Time 17 S/cm
Temp. 320°F 160°C
Max Zero Shift + 23.4% FS



(b)

Variable Inductance
Range 0-100 PSI
Time 17 S/cm
Temp. 250°F 121°C
Max Zero Shift + 4.5% FS

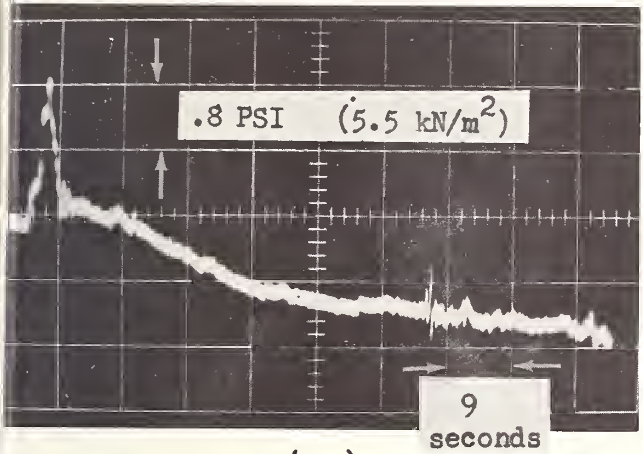
(b) 1st 2.8 minutes



(c)

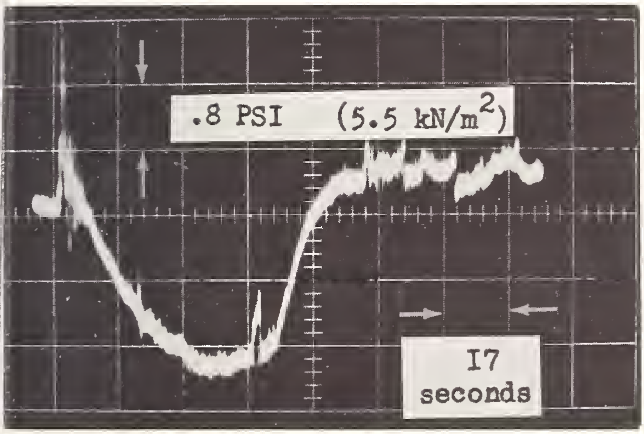
Conditions same as (b)
after 12th minute

Figure 6 Thermal Gradient Response



(a)

Semiconductor Gages
Range 0-100 PSI
Time 9 S/cm
Temp. 193°F 89°C
Max Zero Shift 1.9% FS



(b)

Semiconductor Gages
Range 0-100 PSI
Time 17 S/cm
Temp. 193°F
Max Zero Shift 1.9% FS

Figure 7 Thermal Gradient Response

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